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Spectral response of cotton to suddenly induced water stress

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Abstract. Spectral responses in eight wavebands (three visible, two near-IR, two mid-IR, and one thermal IR) were measured by repetitively traversing a radiometer over several rows of cotton (*Gossypium hirsutum* L.). After an initial measurement, the stems of one row (which had previously been tied to wooden dowels) were cut at a point just above the soil. The subsequent dessication of plants within this row was followed by comparing its reflectance and emittance with a control row. All wavebands measured reacted rapidly to stress with the visible and thermal IR showing a larger change than the near-IR. Reflectance changes caused by canopy geometry changes were apparently greater than those caused by leaf physiological and anatomical changes in all but the visible red band. The increase in red reflectance was attributed to a rapid decrease in absorptance by leaf chloroplasts. As expected, the radiometrically determined plant temperatures increased with time after the stress was imposed.

1. Introduction

Remote-sensing techniques have potential for detecting and quantifying the degree and areal extent of crop stress. Several band widths within the reflected solar and thermal infrared (IR) portions of the electromagnetic spectrum have been used to infer crop condition. The response of reflected visible and near-IR radiation to water stress in vegetation is not well documented (Holben *et al.* 1983), whereas stress detection using radiometrically measured temperatures has received more attention (Jackson 1982).

Some laboratory measurements of leaf spectra have shown that reflectance values in the 0·4–2·5 μm region increased with decreasing leaf water content (Bauer 1975, Knipling 1970). Gausman (1974) demonstrated the effect of dehydration by periodically measuring the spectra of cotton leaves as the leaves dried. Reflectance continuously increased at all wavelengths within the 0·5–2·5 μm region as drying progressed. Carlson *et al.* (1971) found that reflectance at 1·95 and 2·2 μm decreased linearly with increasing relative leaf water content.

A number of complicating factors are involved when laboratory measured leaf spectra are compared with field measured canopy spectra (Bauer 1975). A factor long recognized but studied comparatively little, is canopy geometry. Plant height, number and distribution of leaves, leaf colour and size, leaf angle and epinasty all act in concert to determine canopy geometry. When plants become stressed their leaves may droop, roll and curl, causing the canopy geometry to change. Heliotropic behaviour is also altered by water stress (Ehleringer and Forseth 1980). The net effect is to change the direction of radiance reflected from the leaf surface, sometimes resulting in more radiance being trapped within the canopy. At the same time as the canopy geometry changes, individual leaf reflectance may change because of physiological and anatomical factors (Gausman *et al.* 1969).

Curran and Milton (1983) grew a crop of curled cress (*Lepedium sativum* L.) to provide a plant canopy in a laboratory setting. Reflectance in the red (0·615–0·69 μm) and near-IR (0·78–0·995 μm) wavebands was measured with a radiometer held directly above the canopy. They found that the reflectance in both wavebands increased as the canopy became water stressed, much the same as the laboratory leaf spectra measurements.

In field studies, Tucker *et al.* (1980) demonstrated that red (0·63–0·69 μm) radiance from winter wheat decreased immediately after a drought period was broken by rain. These results imply that red radiance increased as water stress increased. Holben *et al.* (1983) found that the mean reflectance in the near-IR (0·76–0·90 μm) of a soybean canopy decreased with increased water stress. They explained the decrease on the premise that, during wilting, first surface reflections to the sensor would decrease due to leaf droop, resulting in the canopy functioning as a more efficient light trap. Spectral band sensitivity to water stress was reported to be the highest in the near-IR, followed by the water absorption band at 1·55–1·75 μm, and lastly by the visible red band.

Suits (1972) simulated stress conditions by assuming that stressed leaves would droop and change from a horizontal (planophile) to a more vertical (erectophile) position. His model's results predicted an increase in red and a decrease in near-IR reflectance. The difference between these results and those of Curran and Milton (1983) may be due to the fact that curled cress incurred little change in canopy geometry during stress.

When plants become stressed because of insufficient water, physiological reactions and anatomical changes take place that reduce the rate of water loss from leaves. As water becomes less available for evaporation, leaves tend to increase in temperature (Wiegand and Namken 1966). The difference between canopy temperature and ambient air temperature is a useful crop water-stress indicator when used in conjunction with environmental variables such as net radiation and vapour pressure deficit (Jackson *et al.* 1981). The subject of plant temperature and water stress was recently reviewed (Jackson 1982).

We measured the spectral response of field-grown cotton in eight wavebands (three visible, two near-IR, two mid-IR, and a thermal IR) to a suddenly induced water stress for the purpose of determining the sensitivity of these bands to changes in water stress and to compare the relative effects of leaf physiological and anatomical, and canopy geometrical, changes on reflectance as the leaves dehydrated.

2. Experimental

Cotton (*Gossypium hirsutum* L. cv. DPL-70) was planted in north–south rows, about 0·9 m apart. At the time of this experiment, the rows were about 1 m high and about 0·8 m wide, with an effective plant cover of about 90 per cent. The crop had received adequate water and fertilizer throughout the growing season. At the start of the experiment, the air temperature and vapour pressure deficit were 31·4°C and 3·00 kPa, and at the finish they were 34·8°C and 3·77 kPa.

Prior to beginning the experiment, 0·006 m diameter wooden dowels (painted flat black) were inserted vertically into the soil near each plant stem in the central row of three rows of cotton. The cotton plants were tied to the dowels. Care was taken to minimize disturbance of the canopy structure.

A Barnes 12-1000 MMR eight-band radiometer† (see the table) was mounted on a motorized boom that allowed a transect to be made across the cotton rows. The instrument (15° field of view) was held about 1·5 m above ground level. The transect covered 2·64 m, beginning over a Halon reference plate (Schutt *et al.* 1981), moving across three rows of cotton, ending over a 0·03 × 1 m white marker mounted parallel to the row. Upon reaching each end point, the traverse motor was automatically reversed. A run consisted of three complete transverses, or six measurements at any location, and was completed in 15·5 min. The traverse speed was such that a radiometer measurement was made every 0·031 m (1·8 s), giving about 27 data points per row width of cotton. Data from the radiometer were recorded with an Omnidata Polycorder† which was programmed to scan continuously. The traverse time of one run was determined by the time required to fill the Polycorder storage registers.

At 09.00 hours a complete run was made over the intact three row experimental area. The stems of all plants in the central row that had been tied to the dowels were then completely severed with a razor blade near ground level. The result was an abrupt interruption of water flow to the vegetative portions of the plant and, therefore, a sudden imposition of water stress. This operation required about 5 min. A second run was initiated immediately after the stem-cutting operation. Two subsequent runs were initiated about 10 min after completion of the previous run.

Data from the Halon plate were used to convert target data to reflectances. Of the 27 data points per row, the central 13 points (covering about 0·4 m) were averaged for the treatment row and an adjacent row which was used as a control. By using data from the central 0·4 m of the rows, only data from dense vegetation were included in the analysis, and soil background effects were reduced to a negligible level.

3. Results

Reflectance data for the control and the stressed (treatment) row are given in figures 1–3. Note that the ordinate values of figure 3 are 10 times greater than the ordinate values of figures 1 and 2. The temperature data from MMR band 8 are given in figure 4. In the four figures, the 5 min period during which stress was induced is delineated by dashed vertical lines. For the purpose of graphing, it was

Wavelength intervals for the eight-band Barnes 12–1000 MMR and the corresponding Thematic Mapper (TM) bands.

MMR band	Wavelength (μm)	TM band
1	0·42–0·50	1
2	0·52–0·60	2
3	0·63–0·69	3
4	0·76–0·90	4
5	1·15–1·30	—
6	1·55–1·75	5
7	2·05–2·30	7
8	10·5–12·5	6

† Trade names and company names are given for the convenience of the reader and do not imply endorsement by the U.S. Department of Agriculture.

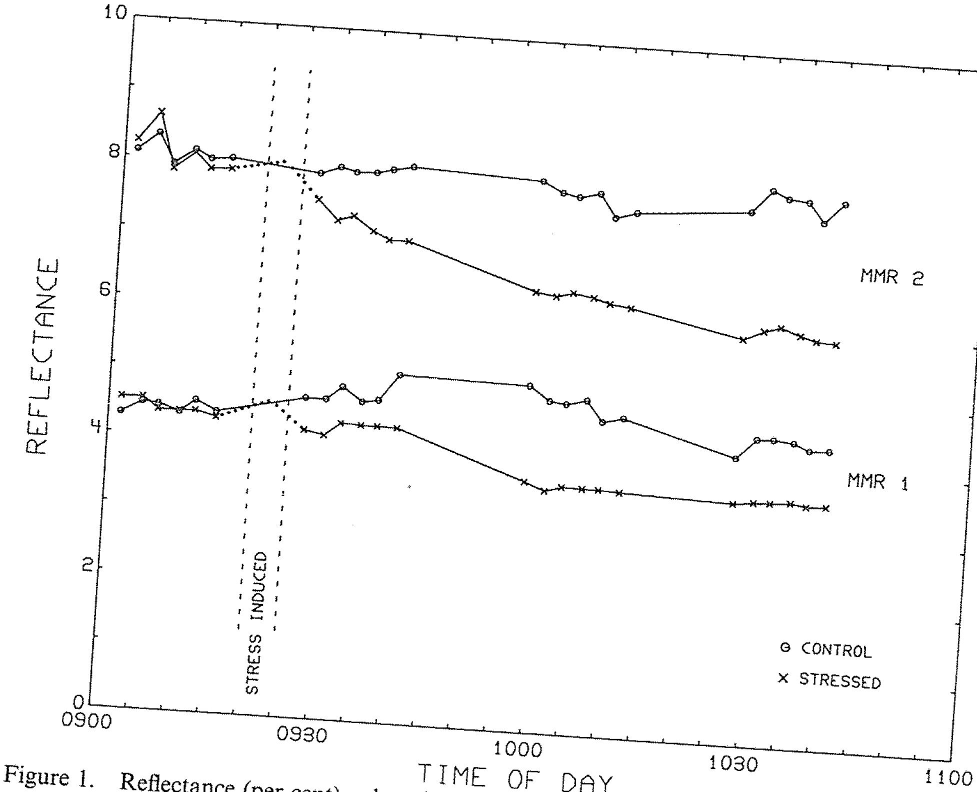

Figure 1. Reflectance (per cent) values for a stressed (×) and a control (○) cotton row for MMR band 1 (0·42–0·50 μm) and MMR band 2 (0·52–0·60 μm), as a function of time.

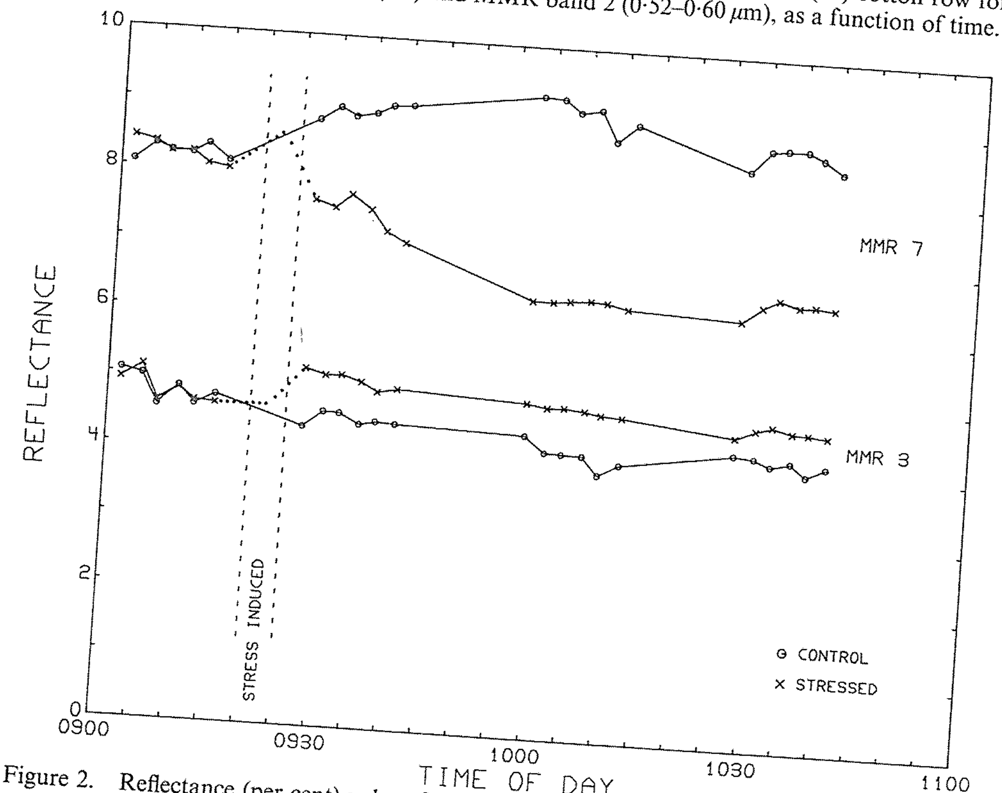

Figure 2. Reflectance (per cent) values for a stressed (×) and a control (○) cotton row for MMR band 3 (0·63–0·69 μm) and MMR band 7 (2·05–2·30 μm), as a function of time.

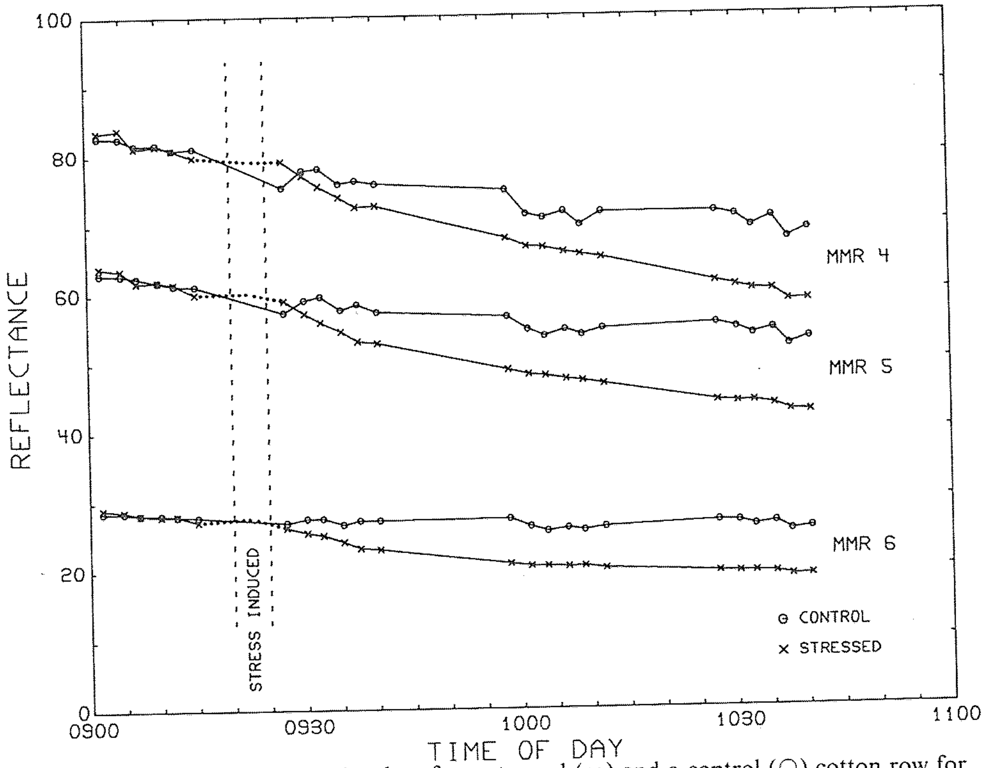

Figure 3. Reflectance (per cent) values for a stressed (×) and a control (○) cotton row for MMR band 4 (0·76–0·90 μm), MMR band 5 (1·15–1·30 μm) and MMR band 6 (1·55–1·70 μm), as a function of time.

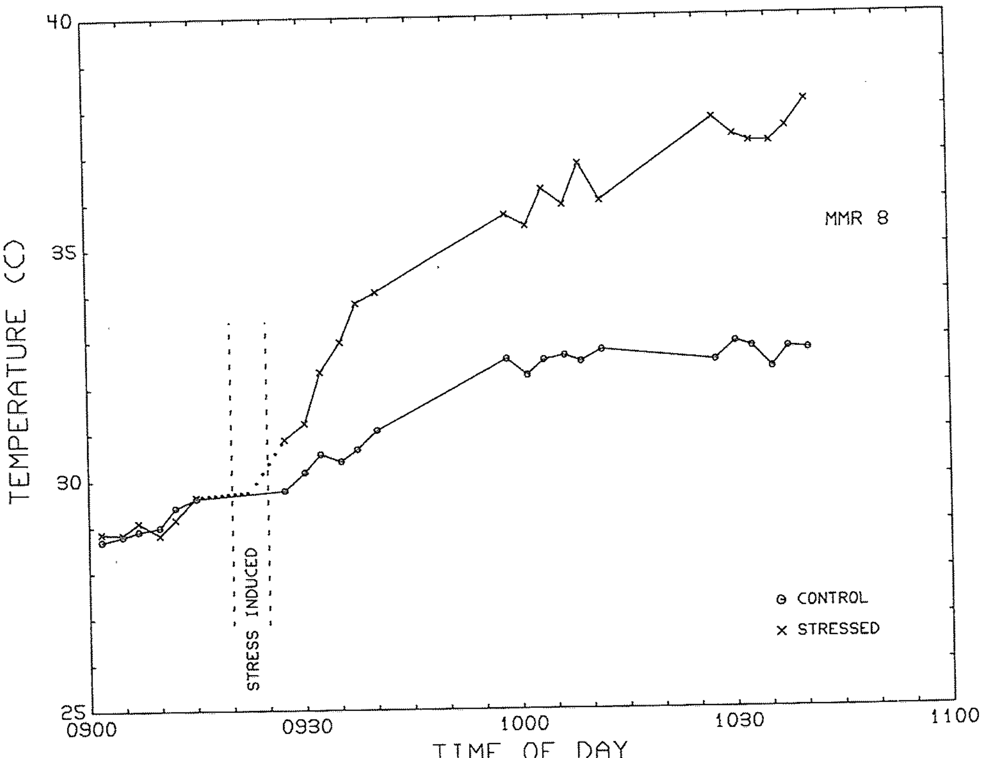

Figure 4. Plant temperatures for a stressed (×) and a control (○) cotton row. Temperatures were calculated from radiance measured in MMR band 8 (10·5–12·5 μm), as a function of time.

assumed that the stressed row would behave the same as the control row until the mid-point of the cutting period. This assumed behaviour is shown by dotted lines. The control row data are indicated by circles and the stressed row data by crosses. The MMR band is identified on the right (see the table for wavelength intervals).

The data for MMR bands 1 and 2 (figure 1) show that these bands responded rapidly to stress. In both bands the reflectance decreased with increasing stress. Figure 2 shows data for MMR bands 3 and 7 (band 7 is out of numerical sequence but is included here to save space). These two bands also responded rapidly to stress as indicated by the first measurement after stem cutting being considerably different from the control. However, MMR band 3 (red) was higher for the stressed than for the control plants. MMR band 7 responded in a manner similar to bands 1 and 2.

Figure 3 gives results for MMR bands 4, 5 and 6. These bands did not respond as rapidly to the induced stress as did the visible bands. For both MMR bands 4 and 5, the stressed row had a higher reflectance than did the control row at the time of the first measurement after stress was induced. After that time the reflectance of the stressed row decreased with time.

Plant temperatures of the stressed row increased rapidly after stress inducement (figure 4). Although the control row increased in temperature until 10.00 hours, the stressed row increased at a faster rate. These results agree with published data (Jackson 1982).

The percentage change due to stress was calculated by dividing the difference between the stressed and the control by the control, then multiplying by 100. This calculation allowed the results from all eight bands to be presented on one graph (figure 5). Positive values indicate that the stressed row had higher reflectances or temperatures than the control row. For clarity of presentation the six scans were averaged to give one value for each set of measurements. MMR bands 3 and 8 were positive, whereas the remaining six bands decreased in reflectance with increasing dehydration.

4. Discussion

Visual signs of leaf wilting were apparent almost immediately after the stems were cut. The apical leaves began to curl and droop, which exposed 'normal appearing' leaves below. Wilting progressed slowly to the lower leaves. Consequently, the geometry of the canopy changed with time. Prior to stem cutting, the leaves were predominantly horizontal. As wilting progressed, the leaf angles became more vertical.

Pinter *et al.* (1979) found that visual signs of wilting in diseased cotton were evident at the same time that a temperature rise was measured by IR thermometry. In sugar-beet, however, leaves of diseased plants showed a marked temperature increase before visual wilting was observed. In both cases the disease was a fungal infection of roots that disrupted sap flow in vascular tissues. Our results, those of Pinter *et al.* (1979) and the data from the curled cress canopy reported by Curran and Milton (1983), illustrate the fact that spectral response to water stress is dependent on species (and perhaps even on cultivar).

Laboratory analyses indicate that spectral reflectance will increase with an increase in water stress because of physiological and anatomical changes within leaves. Field and model results indicate that the reflectance may increase at some wavelengths and decrease at others, depending on the geometry changes that accompany stress. Our results showed that, for this cotton cultivar, geometry

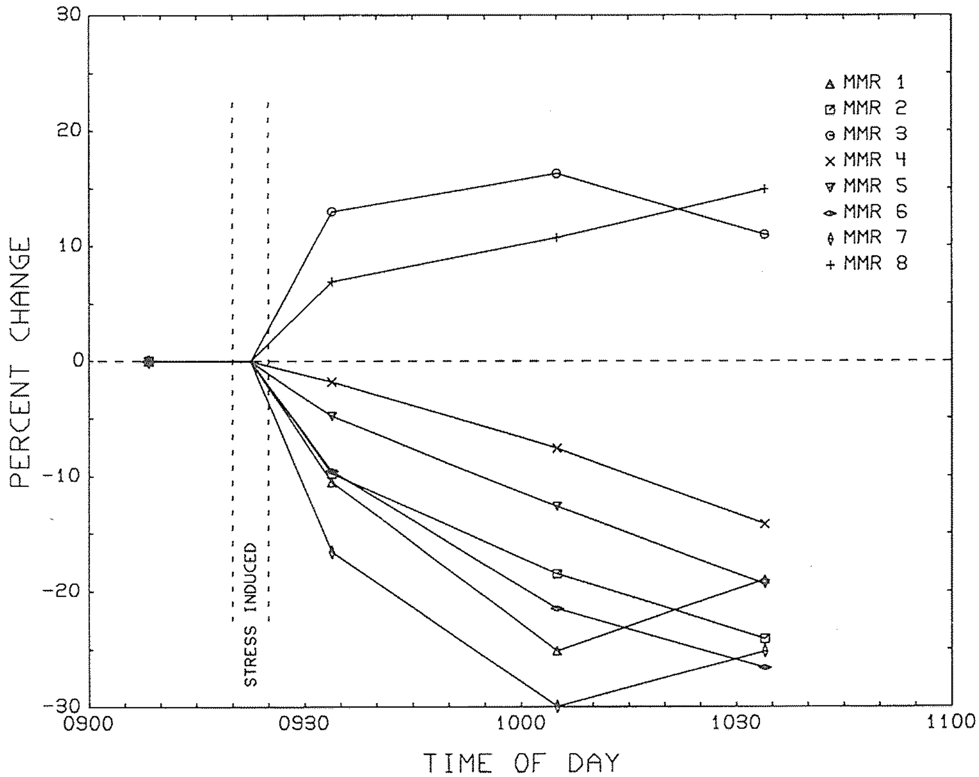

Figure 5. Percentage change as calculated by 100 (stressed − control)/control for seven reflectance and one thermal band, as a function of time.

changes play a major role in determining reflectance properties of canopies. The reflectance of six of the seven reflected solar bands decreased as the cotton leaves dehydrated and as the leaf angles changed from a horizontal to a vertical orientation. Our explanation is similar to that of Holben *et al.* (1983), leaf droop caused first surface reflections to be scattered into the canopy with less radiance reaching the sensor held above the canopy. For the six bands, canopy geometric changes overshadowed the increased reflectance that occurred as a result of physiological and anatomical changes within leaves.

Reflectance in the red (0·63–0·69 μm) chlorophyll absorption band showed a net increase. The same canopy geometrical factors were active, but the physiological changes were apparently greater. Red light is absorbed by green leaves and provides the energy to combine carbon dioxide and water in the complex biochemical process of photosynthesis. In a recent review, Kreig (1983) concluded that a reduction in water availability would first cause a reduction in the biochemical processes which would then trigger the closure of stomata to control the exchange of carbon dioxide and water with the atmosphere. Our hypothesis is that the sudden interruption of the water supply to the leaves immediately affected the absorption of light by chloroplasts in the photosynthesis process, causing the red radiation that was previously absorbed to be reflected or transmitted back to the environment.

On the basis of percentage change, the visible bands reacted as rapidly to a suddenly induced water stress as did the temperature (figure 5). MMR band 7, a water absorption band, decreased by 17 per cent within 10 min of the cutting of the stems, whereas MMR band 3 increased by about 12 per cent within the same time period. MMR band 4, the near-IR, showed the least percentage change. This result is contrary to the results of Holben *et al.* (1983) who found that the near-IR was the most sensitive to water stress. In general, our results support the statement of Knipling (1970) that the visible reflectance region is as sensitive to stress as is the near-IR region.

5. Conclusions

1. Spectral response of plant canopies to water stress is determined by both leaf physiological and anatomical, and plant canopy geometrical, factors. The relative contributions of these factors to the spectral response of canopies are dependent on plant species and possibly cultivars.

2. The increase in red reflectance caused by a sudden interruption in water flow to cotton leaves may be attributed to a reduction in absorbance of red light by chloroplasts. In cotton, the increase in radiation by this mechanism appears to be greater than the decrease that would occur due to canopy geometry changes.

3. Radiation within the reflected solar and thermal-IR regions reacts rapidly to stress. Although the reflectance change in the visible region is as large or larger than in the near-IR and the thermal IR, the reflectance values are so low that the changes may be difficult to detect in an operational mode.

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